ADVANCED REACTOR, FUEL CYCLE, AND ENERGY PRODUCTS WORKSHOP FOR UNIVERSITIES

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Materials

Oak Ridge National Laboratory

Workshop for Universities
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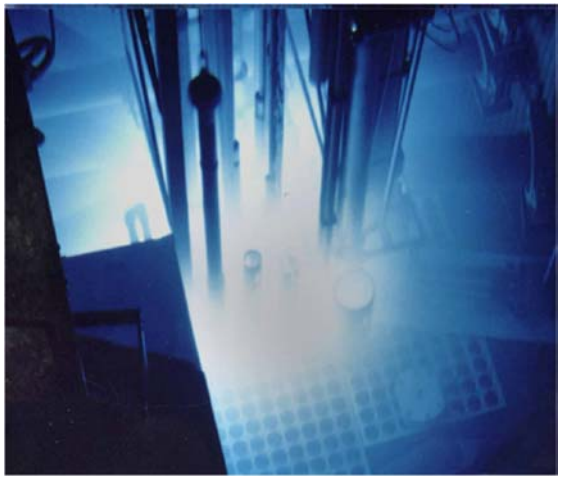
THIS RESEARCH AREA INCLUDES

- Selection, development, and qualification of structural materials needed to design and build the advanced reactors being developed within the Gen IV Reactor Program
- These activities are part of the Gen IV Reactor Program and are closely coordinated with similar structural materials research for the AFCI and NHI Programs
- Materials needs will be addressed for the NGNP, GFR, SCWR, and LFR reactor systems, as well as for their energy conversion systems

Advanced Materials Development and Qualification Essential for All Gen IV Reactors

- Materials Will Be Exposed to High Temperatures, Neutron Exposures, and Corrosive Environments
- 60-Year Operating Lives for Gen IV Reactors Will Require Very Long-Term Materials Stability

- Process-Heat Use for Large-Scale Hydrogen Generation Will Also Require Materials Compatibility with Heat-Transfer Media and Reactants
- Research Will Build upon Extensive Previous Materials Development for Other Reactor Systems and Related Domestic and Foreign Programs



FY03 ACCOMPLISHMENTS

- Gen IV Materials Technology Program Completed Several Assessments of Materials Needs and Development of Materials Selection, R&D, and Qualification Plans
  - NGNP Materials Selection and Qualification Program Plan
  - Survey of Materials Experience and R&D Needs to Assess Viability for SCWR
  - LFR Survey of Materials Research and Development Needs
  - Crosscutting R&D Plan For Development of High-Temperature Structural Design Technology for Gen IV Reactor Systems
  - Modeling and Microstructural Analysis: Needs and Requirements for Generation-IV Fission Reactors
  - Initial Generation IV Reactors Integrated Materials Program Plan

FY03 ACCOMPLISHMENTS

- **Limited Experimental Materials Studies Were Also Initiated**
  - **Currently available nuclear graphites were selected and scoping irradiations begun to assess their suitability for NGNP service**
  - **Initial corrosion testing for SCWR applications demonstrated significant challenges for traditional structural materials in anticipated high-temperature supercritical water environments**
  - **Materials were selected and corrosion exposure begun in Pb-Bi for LFR applications**
  - **Joining studies of advanced ODS alloys were begun for GFR applications**

WORK IN PROGRESS FOR FY04

$3015K, 16 Work Packages, 7 Organizations

1. **Materials for Radiation Service (ORNL)**
2. **Materials for High-Temperature Service (ORNL)**
3. **Microstructural Analysis and Modeling (ORNL)**
4. **High-Temperature Design Methodology (ORNL)**

5.-14. Reactor-Specific Materials Technologies (ORNL, INEEL, ANL, LANL, LLNL, U. of Wisc., U. of Mich.)

15. Materials for Energy Conversion (ORNL)

16. National Materials Program Management (ORNL)

WORK IN PROGRESS FOR FY04

Reactor-Specific Materials Work Packages

- **NGNP Materials–Materials Selection and Qualification Planning and Graphite Irradiations (ORNL, INEEL)**
- **GFR Materials–Materials Selection and R&D Planning, CO_2 Radiolytic Decomposition, and ODS Materials Joining (ORNL, INEEL)**
- **SCWR Materials–Water Chemistry Control, Corrosion and SCC in SCW (ORNL, U. of Wisc., U. of Mich.)**
- **LFR Materials–Materials and Coolant Selection and R&D Planning, Corrosion in Pb-Bi, and Review of Surface Modification and Alternate Corrosion Control Methods (ORNL, ANL, LANL, LLNL)**

MATERIALS CROSSCUTTING PLANS FOR FY05-07

Materials for Irradiation Service

- Perform design of facilities for both low flux and high flux high temperature irradiations
- Initiate initial low-dose scoping irradiations of commercial, near-commercial, and advanced materials and PIE of commercial and near-commercial materials

MATERIALS CROSSCUTTING PLANS FOR FY05-07

Materials for High-Temperature Service

- Complete establishment of initial database for candidate materials for high-temperature and radiation service for all Gen IV reactor systems
- Identify deficiencies in high-temperature materials needed for codification
- Initiate scoping studies of mechanical properties for high-temperature materials
- Initiate joining and combined-effects high-temperature screening studies on commercial and near-commercial alloys and advanced high-temperature materials.
- Initiate preparation of documents of 316FR and alloy 617 for ASME codification.

MATERIALS CROSSCUTTING PLANS FOR FY05-07

Microstructural Analysis and Modeling

- Prepare integrated report prioritizing microstructural modeling needs for Gen-IV reactor program, and identifying needed special-purpose experiments
- Evaluate models for nucleation phase of the significant extended defects produced under irradiation.
- Evaluate overall microstructural evolution under low and high temperature irradiation, include results from preliminary modeling studies and microstructural characterization.
- Initiate microstructural model development in critical areas

MATERIALS CROSSCUTTING PLANS FOR FY05-07

High Temperature Design Methodology

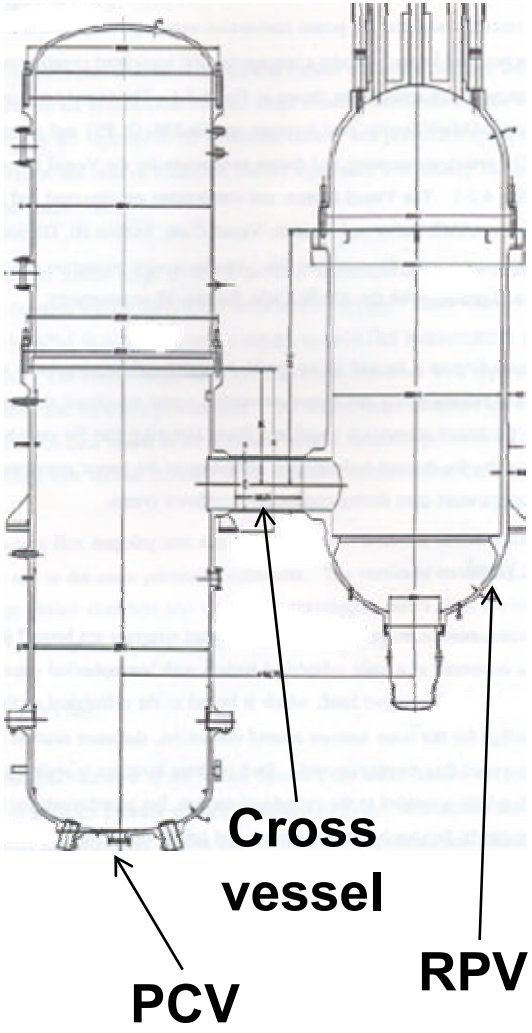
- Initiate development of rules to allow use of low-temperature design criteria for vessels subjected to limited high-temperature service
- Develop interim constitutive equations for modified 9Cr-1Mo steel (Grade 92) and Alloy 617

9Cr-1MoV Is Primary Choice for NGNP Reactor Pressure Vessel System

- Up to 650°C operating temp and 3 x 10^{19} n/cm^2 fluence
- Issues include irradiation effects in creep range, & long-term strength
- High-temperature design methodology needs updating for nuclear service
- Very large vessel sizes will require scale-up of ring forging & joining technologies and ensuring thick-section properties

Correctly scaled size of typical PWR RPV

7 to 9Cr-2WV, 3Cr-3WV, 2 1/4Cr-1Mo, & 12Cr-1MoWV also being evaluated



REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

NGNP Irradiation Studies

- Evaluate the potential effects of low damage-rate neutron environments on the long-term, high-temperature microstructural stability of candidate alloys for NGNP RPV and metallic core components
- Complete design and fabrication of primary irradiation facility for low-flux irradiations for NGNP
- Perform irradiations of preliminary candidate RPV alloys in the low-flux irradiation facility

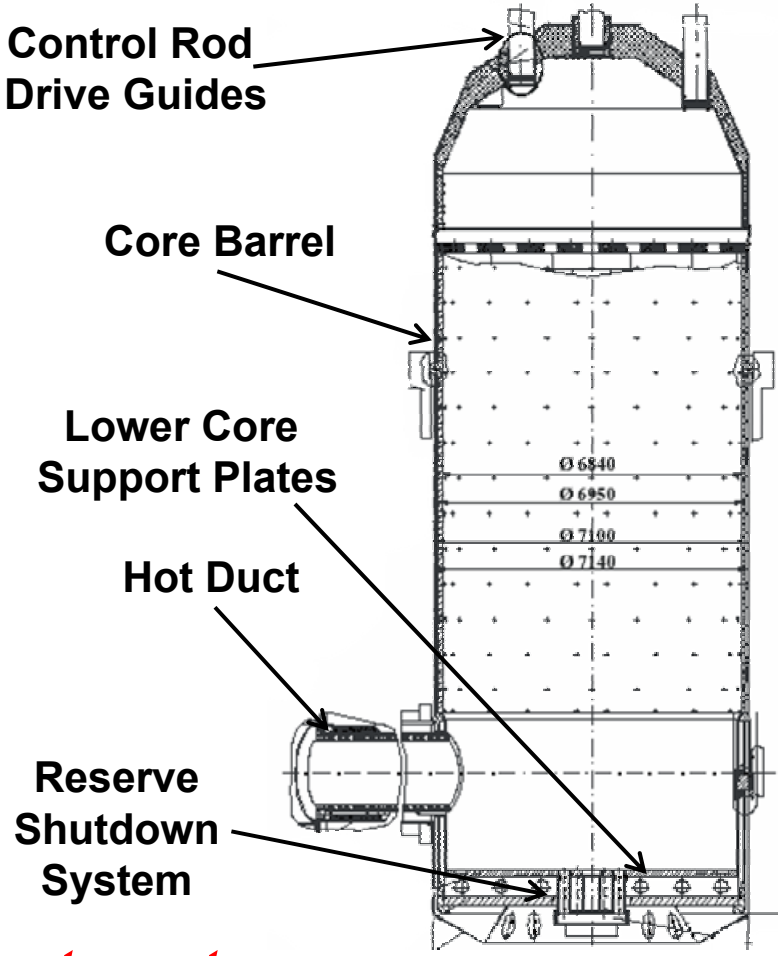
REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

NGNP Irradiation Studies (cont.)

- **Complete design and fabrication of high-flux irradiation facilities for NGNP**
- **Based on spectral and flux distributions for the NGNP metallic core components, define the nature and magnitude of potential radiation effects on the performance of candidate alloys**
- **Complete preliminary irradiations and PIE of potential candidate alloys in high-flux experiments for NGNP**
- **Perform irradiation experiments of metallic internals alloys with a high thermal-to-fast flux for NGNP**
- **Initiate irradiation experiments of primary candidate materials for internal VHTR structures.**

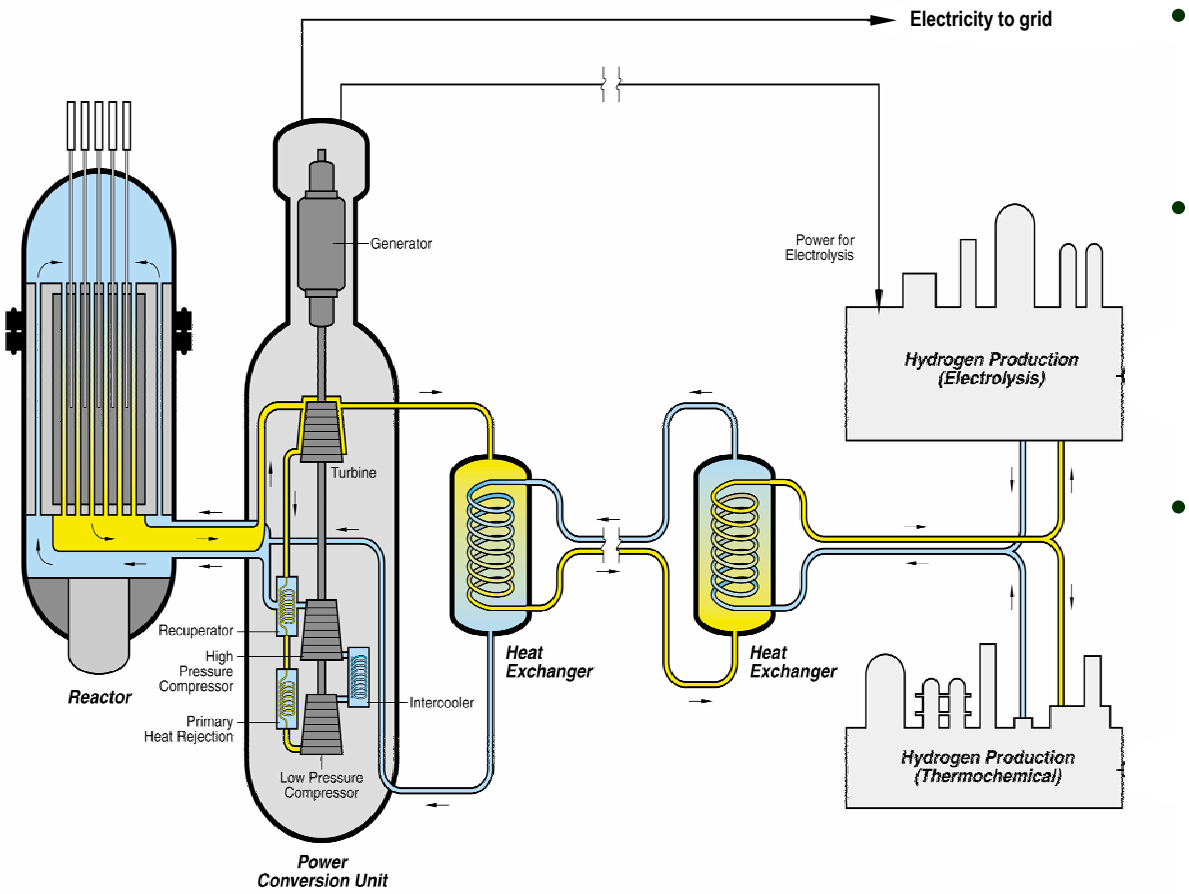
Metallic Reactor Internals in NGNP Will Be Limited to Insulated Components

- Components must withstand moderate irradiation exposure and operating temperatures
  - <5 x 10^{19} n/cm^2 @ ≈600°C
- Very long-term properties, microstructural stability, and coolant compatibility limiting for normal service
- Good candidate alloys exist
  - Alloy 800H or 800HT
  - 316FR
  - Alloy 617
  - Alloy 230
  - Hastelloy X or XR



Off-normal temperatures to 1200°C limit metals use

NGNP Will Contain Multiple Intermediate Heat Exchangers



- Varied materials compatibility needs (e.g. He, molten salt)
- ≈1000°C operation
  - Hi-temp strength
  - Fabrication and joining technology
  - Long-term stability
- Candidate alloys are being evaluated
  - Alloy 800H/HT
  - 316FR
  - Alloy 617
  - Alloy 230
  - Hastelloy X/XR

Material Selection and Qualification Closely Tied to Internals, Piping, etc.

REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

NGNP High-Temperature Materials and Design Methods

- **Select primary high-temperature materials and complete planning needed to qualify alternate materials for NGNP structural components.**
- **Complete time-independent mechanical properties evaluation of commercial and near-commercial alloys for NGNP service**
- **Initiate uniaxial and biaxial creep-fatigue tests and development of creep-fatigue damage model for modified 9Cr-1Mo steel (Grade 92) and Alloy 617.**
- **Initiate mechanical testing of CCM, insulator, metallic reactor internals, bolting, and IHX materials in the NGNP gaseous environment.**
- **Complete initial assessment and provide materials use guidelines for NGNP HX materials**

REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

NGNP High-Temperature Materials and Design Methods (cont)

- **Develop initial simplified high-temperature design rules for use in preliminary design of NGNP components**
- **Evaluate need for, and role of, exemption rules for high-temperature design of proposed NGNP pressure vessel and very-high-temperature component materials and develop rules**
- **Transition constitutive equation development to candidate NGNP pressure boundary materials and NGNP very-high-temperature component materials.**

REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

NGNP High-Temperature Materials and Design Methods (cont)

- **Use interior constitutive equations to develop isochronous stress-strain curves and other predicted behavioral representations for modified 9Cr-1Mo steel (Grade 92) and Alloy 617.**
- **Propose creep-fatigue criteria for modified 9Cr-1Mo steel (Grade 92) and Alloy 617.**
- **Complete Alloy 617 confirmatory structural tests, and initiate testing of models for other key NGNP structural materials**

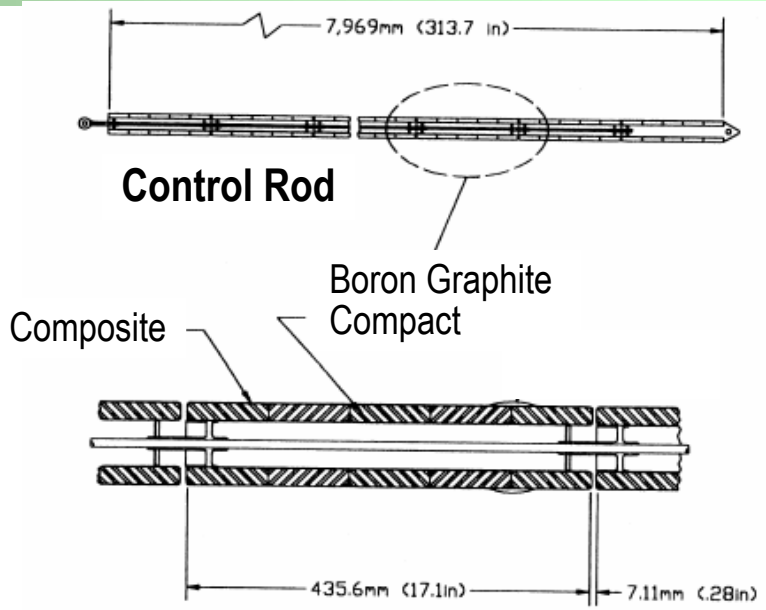
Data for Currently Available Graphites Must Be Developed

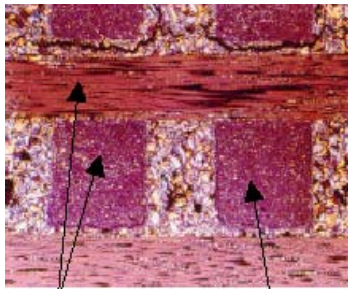
- Operating temps from 750° to 1250°C, off-normal to 1500°C
  - Short-term strength
  - Thermal-physical properties
  - Oxidation studies (He and air)
  - Irradiation degradation and creep
- Fine-grained isotropic and extruded near-isotropic grades are being considered
  - SGL NBG-10 & HLM
  - GrafTek (UCAR) PCEA & PGX
  - Toyo Tanso IG-110
  - Carbone USA 2020
- Design model modifications & verifications and ASME Code approvals needed

Graphite Fuel Element Blocks

Structural Composites Needed for Off-Normal, High-Temp Internals (>1200°C)

- Control rods, upper core restraints, interior insulation covers and supports, as well as hot duct liner
- Composites architectures need to be tailored to and evaluated for each component
- Radiation effects data and design models must be developed for C-C and SiC-SiC control rods
  - VHTR will need to extend to 200°C higher than current data
  - High fluences will limit C-C lifetimes
- Oxidation limits performance during very high temperature air incursions





Fiber bundles

C-C composite microstructure

REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

NGNP Graphite and Composites

- **Complete PIE of NGNP potential candidate graphite scoping irradiations**
- **Complete ASTM standard materials specification development in support of NGNP graphite**
- **Complete purchase of pre-production lot(s) of NGNP candidate graphite(s)**
- **Complete preliminary characterization of baseline physical and mechanical properties of NGNP candidate graphites**

REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

NGNP Graphite and Composites (cont)

- **Complete design and construction of NGNP graphite irradiation creep capsules**
- **Complete graphite physical and mechanical properties evaluations for NGNP**
- **Complete preliminary graphite oxidation effects studies of NGNP graphites**
- **Complete preliminary irradiation effects studies of NGNP graphites**
- **Complete evaluation of as-received properties of candidate C-C composites for control rods, bolting, and insulation materials for NGNP**

REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

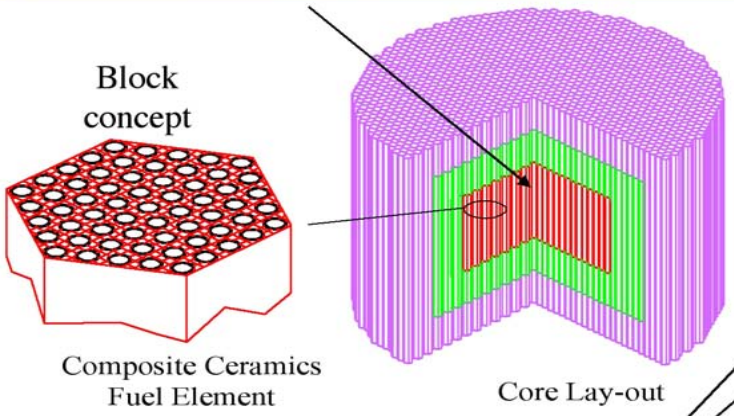
NGNP Materials Compatibility

- **Initiate design and construction of NGNP materials compatibility test facilities and establish required test matrices.**
- **Initiate emissivity testing for NGNP RPV**
- **Complete preliminary evaluations of materials compatibility for NGNP applications**
- **Initiate mechanical testing of pressure boundary and insulation materials in the NGNP gaseous environment.**

To Maintain a Fast Spectrum, GFR Core Cannot Contain Graphite

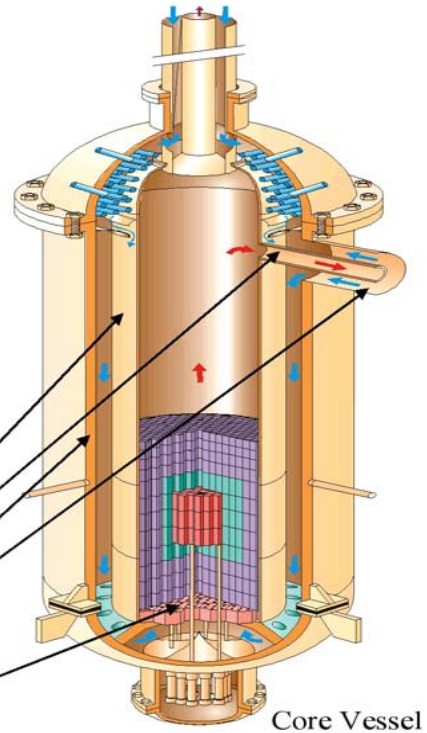
Core structural materials

- -Particles concept: Basket & supporting structures
- -Composite concepts: Hex.canning (block) & casing (plate)
- -Solid solution fuel concept: clad & wrapper
- -Other structures: reflectors & control rods



Internal & vessel structures

- -Gas duct barrel & hot gas duct
- -Reactor vessel & cross vessel
- -Core support components



High-Dose, Fast-Spectrum, Irradiation-Resistant, Low-Carbon Core Materials Are Key

Most Other GFR Materials Needs Will Be Enveloped by NGNP

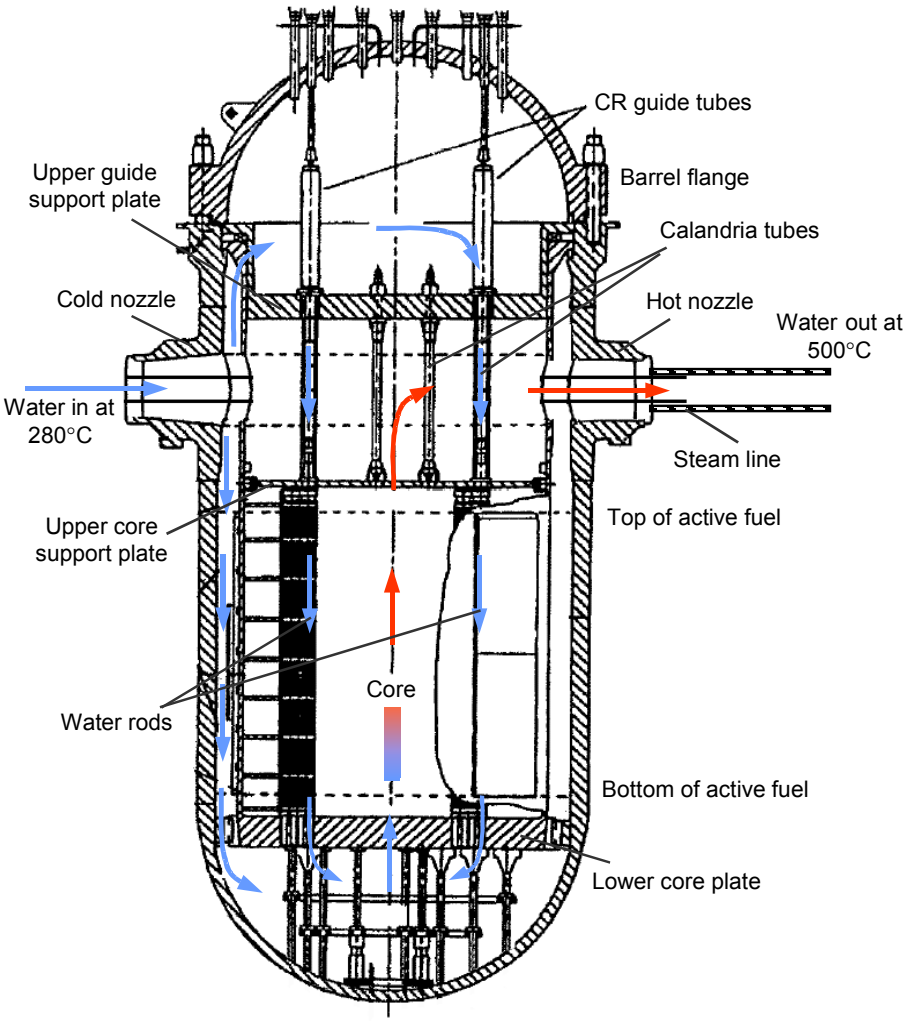
REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

GFR Materials

- Initiate materials compatibility studies of ODS ferritic-martensitic steels, Nb- and Mo-base alloys and ceramics including Nb- and Mo-base cermets with impure helium for GFR
- Initiate materials compatibility studies with super-critical CO_2 in the temperature range of 400 to 650°C for GFR

SCW Corrosion on Internals and BOP Is Greatest SCWR Materials Challenge

- Effect of radiolysis on coolant chemistry
- Effect of radiation and coolant on corrosion, SCC, and IASCC
- Temperatures from 280 to 500°C
- Radiation exposure will further limit internals materials
  - microstructural stability
  - mechanical properties
  - fracture resistance
- Internals candidate materials
  - 304L/316 & low-swelling stainless and F-M steels
- Rotors & disks--1Cr-MoV
- Turbine blades 12Cr-type steels
  - 403 or 422



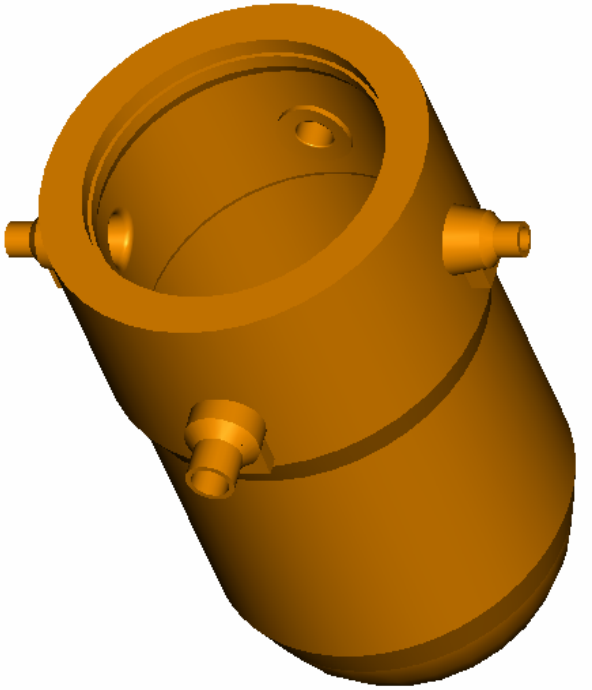
REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

SCWR Materials Compatibility

- Complete compilation of available information on solubility of SCWR power conversion systems candidate materials in supercritical steam
- Perform initial corrosion and SCC screening tests in supercritical water for SCWR
- Initiate corrosion fatigue testing for SCWR pump and power conversion systems materials in supercritical water
- Initiate compilation of available information and perform additional measurements required on solubility of SCWR candidate materials in supercritical steam
- Initiate evaluation of factors affecting condensation and stability of corrosive species in SCWR power conversion systems

Manufacturing Requirements for SCWR Vessel Ring Forgings Stretch Infrastructure

- Maintaining through-thickness mechanical and chemical properties during fabrication is primary challenge
- Inspectability for very heavy sections must be ensured
- Primary candidate material
  - A508 Grade 3 Class 1
- Alternate high-strength materials
  - A508 Grade 4N Class 1
  - 3Cr-3WV



- 280°C wall temperature
- <5x10^{19} n/cm^2 (E>1 MeV)
- 27.5 MPa nominal pressure
- Thickness *46 cm (18") in the beltline region, ~61 cm (24") in the nozzle region*

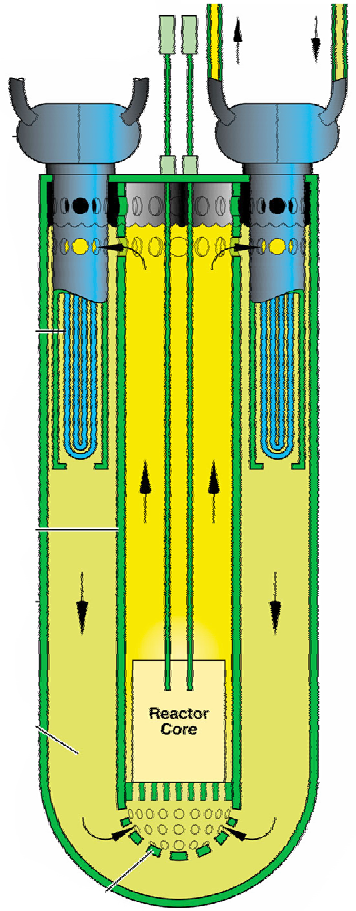
REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

SCWR Irradiations and Vessel Materials

- **Perform initial unirradiated mechanical properties testing of candidate materials for SCWR**
- **Begin scoping irradiation experiments for reactor internals candidate materials for SCWR**
- **Evaluate capabilities of suppliers for thick-section RPV for SCWR and demonstrate fabrication capabilities**

Lead-Cooled Fast Reactor Is Being Evaluated in Several Forms

- Long refueling-interval, transportable system, 50–150 MWe
- Modular system, 300–400 MWe
- Large monolithic plant, 1200 MWe
- Range of Operating Conditions
  - 550-800°C core outlet @ 1 atm
  - Pb or Pb-Bi coolant
  - 150 dpa peak dose
  - 15-30 year core for "battery" concepts
  - Rankine or supercritical CO_2 Brayton cycle
  - Cu-I or Ca-Br thermochemical H_2 production



Materials Compatibility and High-Dose Radiation Resistance for Internals Are Key

REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

LFR Initial Materials Compatibility Studies

- **Establish the extent of additional materials testing needs for compatibility with Pb and Pb-Bi for LFR**
- **Continue scoping studies of preliminary LFR candidate materials for corrosion resistance**
- **Initiate scoping studies of surface treatments for controlling corrosion in LFR environments**
- **Initiate assessment of surface protection mechanisms in LFR materials**

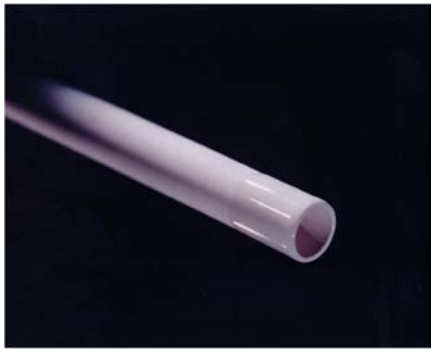
REACTOR-SPECIFIC MATLS PLANS FOR FY05-07

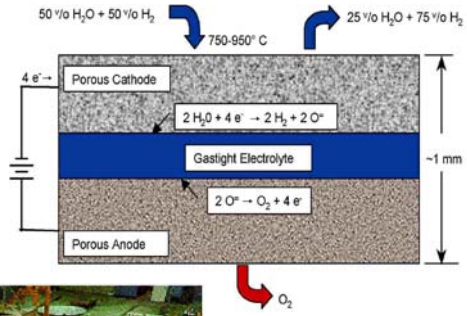
LFR Primary Materials Evaluations

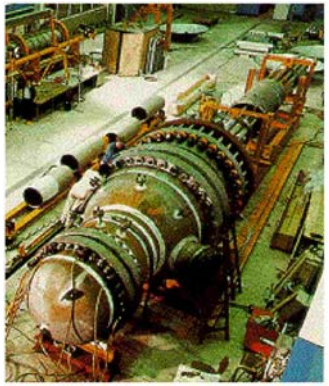
- Complete preliminary selection of primary candidate materials for LFR system
- Initiate assessment of mechanical and corrosion properties of primary candidate LFR materials in as-received condition
- Initiate assessment of creep and aging mechanisms in LFR materials
- Initiate aging and irradiation assessment of primary candidate LFR materials

Nuclear H_2 Generation Materials Must Withstand Harsh Environments

- Thermo-Chemical processes
  - S-I, 950°C vapor to 500°C boiling sulfuric acid
    - Ceramic/noble coatings, sandwich structures
  - Inorganic membranes may dramatically reduce separation temperature
- High Temperature Electrolysis
  - Electrode cost, performance, stability, & fabrication
  - Catalysts
- IHXs for H_2 plant and nuclear/H_2 interface
  - High temperatures for operation and off-normal events
  - Secondary loop(s) coolant type(s)
  - H_2 plant reactants
  - Pressure drops (across IHX and to ambient)
- Intermediate loop piping
  - Temperatures, pressures, and coolant(s)







BUDGETS (FY03-04)

Task	Performer	FY03 Funding (K$)	FY04 Funding (K$)
Materials for Radiation Service	ORNL	171	270
Materials for High-Temperature Service	ORNL	142	75
Microstructural Modeling	ORNL	66	59
High-Temperature Design Methodology	ORNL	76	300
Reactor-Specific Materials Research Coordination	ORNL	26	98
NGNP Materials Planning and Review	INEEL	/	425
NGNP Graphite Irradiation & Matls Planning	ORNL	264	349
NGNP Salt Cooling Matls Assessment	ORNL	/	30
GFR ODS Matls Joining & CO2 radiolysis	INEEL	400	200
SCWR Materials Corrosion Facility	U Mich	/	200
SCWR Materials Corrosion Studies	MIT (03)/U Wisc (04)	50	80
SCW Chemistry Assessment & Control	ORNL	50	100
LFR Materials Assessment	ANL	145	24
LFR Materials Planning	LLNL	/	130
LFR Materials Corrosion in Pb-Bi	LANL	/	235
Materials for Energy Conversion	ORNL	/	19
National Materials Program Management	ORNL	280	421
TOTAL		1670	3015